

N-body Simulations of the Small Magellanic Cloud and the Magellanic Stream

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ABSTRACT

An extensive set of N-body simulations has been carried out on the gravitational interaction of the Small Magellanic Cloud (SMC) with the Galaxy and the Large Magellanic Cloud (LMC). The SMC is assumed to have been a barred galaxy with a disc-to-halo mass ratio of unity before interaction and modelled by a large number of self-gravitating particles, whereas the Galaxy and LMC have been represented by rigid spherical potentials. Our more advanced numerical treatment has enabled us to obtain the most integrated and systematic understanding to date of numerous morphological and kinematical features observed in the Magellanic system (excluding the LMC), which have been dealt with more or less separately in previous studies. The best model we have found succeeded in reproducing the Magellanic Stream (MS) as a tidal plume created by the SMC-LMC-Galaxy close encounter 1.5 Gyr ago. At the same time, we see the formation of a leading counterpart to the Magellanic Stream (the leading arm), on the opposite side of the Magellanic Clouds to the Stream, which mimicks the overall distribution of several neutral hydrogen clumps observed in the corresponding region of the sky. A close encounter with the LMC 0.2 Gyr ago created another tidal tail and bridge system, which constitutes the inter-Cloud region in our model. The elongation of the SMC bar along the line-of-sight direction suggested by Cepheid observations has been partially reproduced, alongside its projected appearance on the sky. The model successfully explains some major trends in the kinematics of young populations in the SMC bar and older populations in the ‘halo’ of the SMC, as well as the overall velocity pattern for the gas, young stars, and carbon stars in the inter-Cloud region.

Key words:galaxies:Magellanic Clouds - galaxies:interactions - galaxies:kinematics and dynamics - galaxies:structure - methods:numerical

1 INTRODUCTION

The interaction between the Large and Small Magellanic Clouds (LMC and SMC) and that between the Clouds and the Galaxy is believed to have markedly influenced the evolutionary development of the Magellanic Clouds as galaxies. These interactions are thought to have produced several observed tidal features such as the Magellanic Stream (MS) and inter-Cloud region (ICR), and distorted the internal structures of the Clouds such as can be seen in the large depth of the SMC (e.g., Caldwell & Coulson 1986) and shell-type features in the stellar distribution of the LMC (Irwin 1991).

Renewed interest in the origin of the MS (see recent papers by Moore & Davis 1994, Sofue 1994, for example) and the continued accumulation of observational data related to the gravitational interaction of the Magellanic Clouds (see Kunkel, Demers & Irwin 1994; Hatzidimitriou, Cannon & Hawkins 1993) have motivated the development of a more advanced model to elucidate the mechanisms ultimately responsible for these features. We have built on the results of the paper by Gardiner, Sawa & Fujimoto (1994), hereafter Paper I, which was in turn based on the model of Murai & Fujimoto (1980), to develop a self-gravitating model of the Magellanic Clouds system. The model we present here is found to match the recent observations by Kunkel, Demers & Irwin (1994) and Hatzidimitriou, Cannon & Hawkins (1993), and also provides novel explanations for other data related to the Magellanic system.

Viable orbits for the Magellanic Clouds about a Galaxy with an extended massive halo were obtained in Paper I and are employed in this present work. The inclination and orbital sense of these Magellanic orbits agree with those determined from proper motion observations of the LMC by Jones, Klemola & Lin (1994). Although the magnitude of the galactocentric transverse velocity of the LMC derived in Paper I (287 kms^{-1}) is larger than that determined by Jones *et al.* ($215 \pm 48 \text{ kms}^{-1}$), subsequent work by Lin, Jones & Klemola (1995) employing their LMC transverse velocity measurement in conjunction with various Galactic potential models leads to a very similar picture for the LMC orbit to that of Paper I. Both Lin *et al.* and the authors of Paper I derived orbits for the LMC with peri- and apo-galactic distances of about 45 and 120 kpc respectively, and thus the interaction dynamics of our simulations are consistent with recent observations.

The simulation of Paper I was able to reproduce the basic observed features of the MS and the ICR, and partially succeeded in determining some effects of the interaction between the Clouds on their internal structure by employing a test particle simulation. Some limitations, however, are encountered in representing the distribution of matter in the Magellanic Clouds by a system of massless particles orbiting in fixed potentials. Chief of these is that the alteration of the form of the potential field due to the deformation of the internal structure of both the Clouds is not taken into account. Secondly, the role of stellar bars in both the LMC and SMC is ignored in the test particle simulation in which the potential is axisymmetric. These considerations led us to develop a self-gravitating model of the Magellanic system in which the total potential field

at a point may be derived from the summation of the forces due to all the constituent particles. As a first application of our self-gravitating model we present simulations of the SMC and its associated tidal products, which include the MS and ICR.

In the following section we present a description of the overall numerical scheme for the system, including the adopted model parameters, and summarise the main features of an equilibrium model for the SMC generated in preparation for the simulation of the Magellanic system. In Section 3 we discuss the overall properties of our simulations and how we searched for a model which best matches the existing observational data. Section 4 is devoted to the description of the best model we obtained. Finally, in Section 5 we state our conclusions and discuss some future applications of our model.

2 THE NUMERICAL METHOD

Our computational model incorporates the basic framework of the model of the Galaxy-Magellanic Clouds system described in Paper I, but instead of representing each of the Magellanic Clouds as a test particle disc in a rigid potential, here we model one of the Clouds by a system of self-gravitating particles. First, we review the general formulation of the dynamics of the Galaxy-Magellanic Clouds system. Then we describe the N -body model used as the initial condition for the SMC.

2.1 The model of the Galaxy-Magellanic Clouds system

In Paper I the model of the Galaxy, LMC and SMC, originally devised by Murai & Fujimoto (1980), was adopted with more recently derived observational parameters in order to reproduce the global distribution of matter in the Magellanic system. The Galaxy potential used was that due to a spherical mass distribution possessing a flat rotation curve out to more than 200 kpc from the Galactic Centre. The LMC and SMC were represented by Plummer-type potentials. The Magellanic Clouds were considered to experience a dynamical friction force due to their motion through the dark halo of our Galaxy. Numerous test particle computations were carried out which enabled suitable orbital parameters for the Magellanic Clouds to be determined by modelling the MS and inter-Cloud region. In Table 1 we summarise the observational parameters used in the model and list the estimated current space velocities of the Magellanic Clouds obtained from this modelling. Additional model parameters to be employed in the present work, and which are discussed in the following subsection, are also tabulated.

Our present numerical scheme differs from the simulations of Paper I in that we do not calculate the evolution of both Clouds simultaneously. Instead we perform separate computations for each of the Magellanic Clouds, constituting one of the Clouds as a self-gravitating particle system and representing the gravitational influence of the Galaxy and the other Cloud by fixed potentials identical to those used in Paper I. Hereafter we denote one of the Magellanic Clouds, that which is represented by a particle system, as ‘Cloud 1’, and the Cloud represented by the fixed potential as ‘Cloud 2’. Our procedure is described as follows:

1. We construct an equilibrium model for Cloud 1 (the ‘equilibrium run’, see Section 2.2) and

subsequently place it at the origin of a non-inertial Cartesian coordinate system centered on Cloud 1.

2. The orthogonal axes of this non-inertial coordinate system are oriented such that the disc of Cloud 1 is coincident with the $x - y$ plane and the z axis coincides with the rotation axis (the axis of the spin angular momentum vector) of Cloud 1. In the general case, the orientation of the non-inertial system relative to the inertial (galactocentric) system is specified by the direction of the rotation axis with respect to the galactocentric system (X, Y, Z) . Two angles, θ and ϕ , defined in the spherical polar coordinate system in the usual way (see Fig.1), determine the relationship between the two systems.

3. Based on the orbits derived in Paper I for the time interval from $T = -2$ Gyr to $T = 0$ which corresponds to the current epoch, we create a look-up table of positions and velocities for the Galaxy and Cloud 2 in our non-inertial system (x, y, z) . The timestep used has a duration of 2×10^6 yr giving 1000 timesteps for the complete simulation.

4. Cloud 1 is evolved from $T = -2$ Gyr towards the present under the influence of external forces due to the Galaxy and Cloud 2 (the ‘interaction run’).

5. In the present paper we take the SMC to be Cloud 1 and the LMC to be Cloud 2. The particles in Cloud 1 are assumed to be collisionless. Then the complete expression for the total force applied to an individual particle in Cloud 1 is given by:

$$\ddot{\mathbf{r}}_i = -\frac{G}{m_i} \sum_{j \neq i}^n \frac{m_j(\mathbf{r}_i - \mathbf{r}_j)}{(|\mathbf{r}_i - \mathbf{r}_j|^2 + \epsilon^2)^{3/2}} + \mathbf{F}_{Gal}(\mathbf{r}_i - \mathbf{r}_{Gal}) + \mathbf{F}_{lmc}(\mathbf{r}_i - \mathbf{r}_{lmc}) - \mathbf{F}_{Gal}(-\mathbf{r}_{Gal}) - \mathbf{F}_{lmc}(-\mathbf{r}_{lmc}), \quad (1)$$

where \mathbf{r}_i denotes the position vector of the i -th particle in the coordinate system (x, y, z) centered on Cloud 1, m_i is the particle mass, and G is the gravitational constant. The softening parameter is denoted by ϵ and is discussed later. The positions of the Galaxy and the LMC in this coordinate system are denoted by \mathbf{r}_{Gal} and \mathbf{r}_{lmc} , respectively, and these should be understood as given functions of time. We assume that the gravitational potential of the Galaxy is one which gives a flat rotation curve with a constant circular velocity, V_0 ($=220 \text{ kms}^{-1}$), out to beyond 200 kpc from the Galactic Centre so that the gravitational force of the Galaxy exerted on a particle of unit mass is given by

$$\mathbf{F}_{Gal}(\mathbf{r}) = -\frac{V_0^2}{|\mathbf{r}|^2} \mathbf{r}. \quad (2)$$

The LMC is assumed to have a Plummer-type potential with an effective radius, K ($=3$ kpc), giving a gravitational force on unit mass of

$$\mathbf{F}_{lmc}(\mathbf{r}) = -\frac{GM_{lmc}\mathbf{r}}{(\mathbf{r}^2 + K^2)^{3/2}}, \quad (3)$$

where M_{lmc} is the total mass of the LMC and $\frac{1}{4}$ taken to be $2 \times 10^{10} M_\odot$. The last two terms in

equation (1) are the correction terms which arise from integrating the equations of motion in a *non-inertial* coordinate system centered on the SMC. It should be noted that in the present formalism the effects of dynamical friction are implicitly included in the time development of \mathbf{r}_{Gal} and \mathbf{r}_{lmc} .

Fig. 1

2.2 Equilibrium model for the SMC

As discussed in the previous subsection, we first constructed an equilibrium model for the SMC as Cloud 1. Here we discuss some choices in the physical parameters adopted for the equilibrium model.

a) Global structure of the SMC

We constructed an equilibrium model for the SMC as a two-component system consisting of a nearly spherical halo and a rotationally supported disc. Apart from the fact that such a two-component system represents a good approximation of a real disc galaxy, it facilitates the comparison of the numerical results with the observational data for objects of various age groups such as horizontal-branch stars (belonging to the halo) and Cepheids (belonging to the disc).

Both the halo and the disc are truncated at a radius of 5 kpc (the disc radius). The tidal radius of the SMC, r_t , is given by

$$r_t = r_p \left[\frac{M_{smc}}{(3 + e)M_{Gal}} \right]^{1/3} \quad (4)$$

(Faber & Lin 1983), where r_p is the perigalactic distance of the SMC, M_{smc} is the mass of the SMC, and M_{Gal} is the mass of the Galaxy contained within r_p . Here the orbital eccentricity, e , is given by $e = (1 - b^2/a^2)^{0.5}$, where a and b are the semimajor and semiminor axes of a pseudo-ellipse, respectively. Note that the orbit is not an exact ellipse because the Galaxy potential is not that due to a point mass. The orbital data give values of 43 kpc and 0.89 for r_p and e respectively. The formula yields a tidal radius of 5 kpc for the SMC, which is equivalent to the adopted truncation radius.

In this present work we use an SMC mass of $3 \times 10^9 M_\odot$, compared to $2 \times 10^9 M_\odot$, used in Paper I. If we assume that the MS and ICR originate from the disc component of the SMC and consider the gas associated with the SMC itself to belong to the disc component, we have a combined mass of about 1.3×10^9 for the original disc gas (Westerlund 1990). In addition,

the stellar disc component may also contribute to the total disc mass making the original disc mass of the SMC significantly greater than $1.3 \times 10^9 M_\odot$. Evidence for the existence of a halo component in the SMC comes from the spheroidal kinematics of carbon stars (Hardy, Suntzeff & Azzopardi 1989) and planetary nebulae (Dopita *et al.* 1985). Regrettably, no reliable estimate for the halo mass (possibly including invisible matter) out to the adopted disc radius is available at the moment. If we take a disc-to-halo mass ratio of 1:1, then the total mass of the SMC in the pre-encounter phase is at least $2.6 \times 10^9 M_\odot$. This consideration led us to take a relatively large mass for the SMC. It should be pointed out that, due to the much smaller mass of the SMC relative to the LMC and the Galaxy, the SMC's orbital motion is nearly independent of the SMC mass.

The global structure and evolution of a model disc galaxy are largely determined by two non-dimensional quantities, the disc-to-halo mass ratio and the turnover radius of the rotation curve relative to the disc radius. The mass ratio between the disc and halo components can dramatically alter the evolution of a system in an isolated state. A stellar disc having a mass comparable to or larger than that of the halo is known to develop a bar in a few rotations (e.g., Ostriker and Peebles 1973). Unfortunately, a reliable estimate of this important parameter for the SMC *in the pre-encounter state* is quite difficult to obtain. We have chosen to use a disc/halo mass ratio of 1:1, because a number of disc galaxies with reliable observational data have been shown to have a mass ratio of around unity (e.g., van der Kruit & Searle 1982). It should be borne in mind that the possibility of a smaller mass ratio, and hence a pre-encounter disc stable against spontaneous bar formation, cannot be ruled out. We assume that the surface density distribution of the disc obeys an exponential law with a scale length of 0.25 times the disc radius as suggested for most disc galaxies (e.g., Fall 1980).

Another important parameter characterising the equilibrium model is the turnover radius of the rotation curve. This is the radius at which the rotational velocity changes from that of nearly rigid rotation to a nearly constant value. Numerical studies (e.g., Sellwood 1981) indicate that the length of the spontaneously induced bar has a strong positive correlation with the turnover radius. The turnover radius has been set to a relatively large value of 3.5 kpc (i.e., 70 percent of the disc radius) since a galaxy of the Magellanic type (i.e., a low-luminosity galaxy of very late morphological type) generally has a slowly rising rotation curve from the center to the edge (e.g., Rubin *et al.* 1985). These choices in the adopted parameters allow the generation of a stable bar ~ 5 kpc long in the isolated model as we see below.

b) Equilibrium run

We initially distributed 10000 particles in the disc component and 5000 particles in the halo since we are mainly interested in the disc particles, which, due to their smaller random motions, tend to form finer structures than the halo particles. This means that in our calculations the mass of an individual halo particle is twice that of a disc particle given a disc/halo mass ratio of unity. In the calculation of the gravitational force we used the tree-code (e.g., Barnes and Hut 1986). The gravitational softening length, ϵ (see equation (1)), to suppress undesirable two-body

effects was taken to be 50 pc.

The equilibrium run was divided into two stages. First, only the halo particle system was evolved with the disc particle system fixed. During this stage, the halo particles experience the gravitational force of the disc in addition to that of the halo itself, but the disc component does not respond to the change of the total gravitational field. The halo was found to reach a near-equilibrium state after several dynamical times. After this we calculated the gravitational force (arising from both the halo and the disc components) acting on each disc particle. Each disc particle was then given a rotational velocity and a small random motion which corresponds to the Toomre's (1964) Q value of 1.5 so that in the absence of any instability or external perturbation it would move on a nearly circular orbit in balance with the gravitational force. The resultant rotation curve is slightly different from the initially specified one due to a small change in the halo density distribution.

Then the second stage was performed in which all the halo and disc particles were moved under their own gravity. It was found that the disc quickly forms a bar structure within two disc rotation periods in accordance with many previous studies. After having fully developed, the bar did not significantly alter its shape or angular velocity (pattern velocity). Therefore we adopted the state after about 4 rotation periods as the initial condition for the interaction simulations described in the following. Fig.2 plots the spatial distribution of the disc and halo particles separately for this initial state. The halo is nearly spherical whereas the disc develops a strong bar with a length of ~ 5 kpc. Non-circular motions along elongated orbits in the disc plane dominate the disc after the bar has fully developed, whereas the halo is mainly supported by random motions.

Fig. 2

3 INTERACTION SIMULATIONS

In the interaction runs, the SMC model is evolved under the influence of external forces due to the Galaxy and the LMC, starting from the initial condition mentioned above.

3.1 General trends

The first important step was to determine the spatial orientation angle (θ, ϕ) of the SMC disc. If the disc orientation is changed, the orbits of the Galaxy and the LMC in the SMC-centric coordinate system should be correspondingly adjusted. We decided to use a different initial spatial orientation for the disc of the SMC from that used in the test particle computations of

Paper I. Owing to the overall irregular structure and highly disturbed internal kinematics of the SMC, the correct orientation to use is far from clear. In Paper I the authors adopted a disc orientation parallel to the galactocentric $X - Z$ plane consistent with de Vaucouleurs' (1960) determination of the inclination and major axis of the SMC from star counts. (This orientation is specified by $\theta = 90^\circ$, $\phi = 270^\circ$ in our system.) However, with this orientation the SMC bar would lie parallel to the sky plane, but according to the observations of Caldwell & Coulson (1986), we require the bar to be mainly oriented along our line-of-sight in its final position. To satisfy this requirement for the bar, as well as the requirement that the major axis of the disc be oriented along the observed major axis, we adopted a disc spatial orientation specified by $\theta = 45^\circ$, $\phi = 230^\circ$. It turned out that the bar is located nearly in the original disc plane at the present epoch in all the models calculated, and thus it was possible with this disc orientation to produce simulation results in which the bar is oriented mainly along our line-of-sight. On the other hand, we could not construct any satisfactory models by adopting $\theta = 90^\circ$, $\phi = 270^\circ$ (see Section 4.2). It is to be noted that the adopted values of $\theta = 45^\circ$, $\phi = 230^\circ$ may not comprise a unique solution but could be one of a number of possible space orientations.

The final orientation of the bar with respect to our line-of-sight will depend also on the initial orientation of the bar within the SMC disc plane (i.e., the $x - y$ plane of the SMC centric coordinate system). Hereafter, the angle between the bar major axis (at the beginning of an interaction run) and some defined axis in the $x - y$ plane is referred to as the bar position angle. This angle is a free parameter in our simulations. In order to achieve the best fit of the bar spatial orientation to the observations we therefore generated a series of models with different initial bar position angles (keeping $\theta = 45^\circ$ and $\phi = 230^\circ$). We have carried out 12 simulations for bar angles separated by an interval of 30° . From now on we denote a model with its three parameters, θ, ϕ and p , as $\theta/\phi/p$, where p is the initial position angle of the bar. For example, the model 45/230/180 has $\theta = 45^\circ$, $\phi = 230^\circ$, and $p = 180^\circ$. For each of our 12 models with different initial bar position angles, we constructed a series of plots to identify the model which best fits the observational properties of the Magellanic system. The plots constructed were based on Figs 6, 7 and 13 from Paper I. Using these plots, we looked for good geometrical structure in the simulated Magellanic Stream, and good agreement of the spatial orientation of the bar and the appearance of the SMC projected on the sky plane with the observations. It was found that the morphology of the MS displayed a satisfactory agreement with the observed geometry and was largely independent of the initial bar position angle. Therefore the main consideration which determined the choice of our best model was the agreement of the spatial orientation of the bar with observations. All models produced a well developed leading arm on the opposite side of the MS, which is discussed in detail in Section 4.2. Pairs of models with their initial bar position angles differing by 180° were found to have similar bar orientation at the present epoch, reflecting the nearly bi-symmetrical nature of the initial barred model. A bar orientation which matched the observations was best reproduced for $p = 270^\circ$ or 90° and it was decided to adopt model 45/230/270 as the best model.

3.2 Interaction dynamics

Detailed discussion of the best model is postponed to the next section. Nevertheless, it is worthwhile to mention here some aspects of the SMC-LMC-Galaxy interaction in the best model. Fig.3 shows the orbits of the Galaxy and LMC around the SMC in the SMC-centric coordinate system ($\theta = 45^\circ$, $\phi = 230^\circ$) along with the time evolution of the separation between the SMC and the Galaxy or the LMC. The positions corresponding to the times at which the LMC-SMC separation takes a local minimum are marked on the orbits. The SMC disc rotates counterclockwise in the $x - y$ plane. It is seen that both the Galaxy and LMC orbits are roughly polar. The relative orientation of the SMC disc is thus not the most favourable for tidal distortion but we can still expect a significant tidal effect when the Galaxy and/or the LMC pass by the SMC at a small distance. Although the Galaxy-SMC separation always stays larger than the LMC-SMC separation, the more relevant quantity here is the strength of the tidal force, which is depicted in Fig.4. The tidal force in Fig.4 has been calculated by differentiating the gravitational potential of the indicated galaxy twice. In other words, we calculated the gradient of the gravitational force. This gradient gives the relative strength of the tidal force if the perturbed body (the SMC in this case) has a constant size. Although this condition is not satisfied exactly in practice, Fig.4 is still instructive. It is clear that at $T \sim -1.5$ Gyr, when both the Galaxy and the LMC pass the peri-SMC points, the tidal forces due to the Galaxy and the LMC are comparable in magnitude. The MS starts to develop roughly at this epoch. It is therefore suggested that the early development of the MS is governed by the combined effect of the Galaxy and the LMC. At $T \sim -0.2$ Gyr, both the Galaxy and LMC make second close encounters with the SMC. The LMC tidal force is much stronger than that of the Galaxy at this epoch, and is thought to have played a major role in the shaping of tidal features in this most recent epoch.

Fig. 3

Fig. 4

4 THE BEST MODEL — COMPARISON WITH OBSERVATIONS

4.1 Global features of the model

In this section we discuss the simulation results for the best model, with parameters 45/230/270. We first show plots of the global structure produced by the simulation to define our terminology. In Fig.5(a,b) we have plotted, for both disc and halo components, the particle positions in the SMC-centric $x - y$ plane at $T = 0$, namely the current epoch. The various features produced by the interaction of the SMC with the Galaxy and LMC are labelled on the plot for the disc component (Fig.5a), namely the Magellanic Stream, leading arm, and tidal bridge and tail. The tidal bridge and tail were generated by the close encounter between the Magellanic Clouds about 0.2 Gyr ago, while the MS and the leading arm originated at an earlier epoch corresponding to the time of the previous perigalactic approach of the SMC, and coincidentally the time of another close encounter between the Magellanic Clouds about 1.5 Gyr ago. Examination of the best model (see section 4.3) reveals that the tidal bridge and tail are seen to a large extent overlapped in the sky, with the tail section more distant than the bridge, thus giving rise to the inter-Cloud region. The halo component plot (Fig.5b) shows several differences from the disc component plot, including a much less conspicuous stream at the the position of the MS and a less well-defined leading arm.

Before embarking on a detailed discussion of the simulation results in the following subsections, we here present an overview of the relationship between our best model and the results of previous simulations by other workers. Previous simulations of the Magellanic Clouds system have largely aimed at reproducing the geometry and kinematics of the MS, with the notable exceptions of those produced by the authors of Paper I and by Kunkel, Demers & Irwin (1994) (KDI), in which the emphasis was on the internal structure of the Magellanic Clouds. A consensus emerged in the early 1980s on the basic type of *tidal* model required to realistically simulate the observational characteristics of the MS. (Other models for the MS based on ram pressure stripping have also been proposed — see e.g., Moore & Davis 1994, Sofue 1994.) The simulations of Lin & Lynden-Bell (1982) and Murai & Fujimoto (1980) (MF) settled on models in which the Galaxy has an extended massive halo and the Magellanic Clouds have polar orbits with the Clouds leading the MS. The dynamics of the Galaxy-LMC-SMC system in our model are fundamentally similar to those of MF, and therefore our present model of the MS can largely be considered as a refinement to the existing picture. We do, however, present a more convincing interpretation of the leading arm feature than in previous work (see next subsection). Although two sets of models by Fujimoto & Sofue (1976, 1977) have claimed to reproduce the leading arm as tidal debris from the LMC and SMC, these models could not simultaneously achieve a good reproduction of the MS. One of the models by Tanaka (1981) (see his Fig.5c) gives a fairly good reproduction of both the MS and the leading arm as tidal debris from the SMC, but the radial velocity of the tip of the MS is more positive than observed and the resulting leading arm (this is the tidal tail in his model in which the Magellanic orbits are of opposite sense with respect to our model) forms a narrow line unlike the scattered distribution of the real H I clouds.

A number of previous models have considered the internal structure of the Magellanic Clouds by treating the LMC and SMC as separate entities. This approach contrasts with one in which the Clouds are considered as a single-entity (e.g., Lin & Lynden-Bell 1982). MF simulated the region between the Magellanic Clouds (ICR), and their simulation also indicated that the SMC was greatly extended along the line-of-sight direction. In Paper I the authors used a much larger number of particles in their test particle simulation than in MF and treated the structure of the Magellanic Clouds in greater detail. The key feature of their model was the generation of a tidal bridge and tail system which could qualitatively reproduce the inter-Cloud region and the large line-of-sight extension of the SMC. In our N -body simulation based on the same orbital dynamics as Paper I we have also generated similar structures.

The model of KDI also generated a bridge-tail structure with several similar features to the present model. The basic dynamics of their model are different from ours in that they have neglected the gravitational influence of the Galaxy and have adopted an unbound orbit of the SMC with respect to the LMC. Thus the formation of the MS was inevitably excluded from their discussion. Their simulations have led to a different interpretation of the kinematics of the inter-Cloud region from ours, but nevertheless their model reproduces some aspects of the structure and kinematics in the eastern part of the SMC and the ICR (see Section 4.4).

To summarise, the global structure of our model has much in common with previous models, but is the first to *simultaneously* explain many structural and kinematical features of the Magellanic system in a single model. The greater sophistication of our model, which includes particle self-gravity and a two-component disc/halo system representing the SMC, enables it to address a wider range of observational data than previous simulations. We now analyse in detail the simulation of different aspects of the Magellanic system by dealing with the MS, the SMC and the ICR in turn. We have used a combination of techniques adopted in Paper I and newly developed methods to compare the simulation results with observations.

Fig. 5

4.2 The Magellanic Stream

The MS is a narrow band of neutral hydrogen emerging from near the Magellanic Clouds and extending for more than 100 degrees in the sky. It is generally believed that it is a tidal feature produced as a result of the interaction between the Magellanic Clouds and the Galaxy. The first successful attempts to model the MS as tidal debris torn from the Magellanic Clouds were those of Murai & Fujimoto (1980) and Lin & Lynden-Bell (1982). These investigators

surmounted the problem of achieving high negative radial velocities at the tip of the MS by introducing a Galaxy with a massive halo. In Paper I some major characteristics of the MS were also obtained in a reproduction that is fundamentally similar to that of Murai & Fujimoto (1980). The geometrical appearance of the simulated Stream projected on the sky, however, was not as satisfactory as one might have hoped, and therefore in this first application of the self-gravitational model of the Magellanic system we sought to achieve rather better agreement with the observational features of the MS. Although fundamentally the collisionless disc particles of our simulation should represent the *stellar* disc component, it can be considered that in areas of low particle density such as the MS, the collisional and dissipative nature of the gas is not strongly manifested and therefore a collisionless model is adequate for modelling the gaseous MS.

a) Geometry of the Magellanic Stream

In two main respects the model Stream in Paper I failed to match the observations closely. First, the model Stream emerged rather near the LMC on the plane of the sky, whereas in reality it begins near the SMC. Second, the model Stream was rather poorly populated when compared to the observations, especially at the start of the Stream. Our self-gravitating simulations for the spatial orientation ($\theta = 90^\circ$, $\phi = 270^\circ$), corresponding to that used in the test particle simulation, similarly produced a model Stream originating from near the LMC instead of the SMC. However, for our best model (parameters 45/230/270) these deficiencies are overcome, as we will see shortly. In Fig.6 we show, for our best model, a plot of the distribution of disc particles (right panel) compared with the neutral hydrogen distribution (left panel) of the MS projected onto the sky centred on the South Galactic Pole. The plot of the distribution of neutral hydrogen shows data taken from Mathewson & Ford (1984) plus other observations of H I clumps on the opposite side of the Magellanic Clouds from the MS. These latter observations made with coarser resolution were derived from Mathewson, Cleary & Murray (1974) and the data are indicated by the thicker curves on the plot.

Using Fig.6, we see that a well defined stream of particles extending over ~ 100 degrees in the plane of the sky emerges from the ICR near the SMC, in better agreement with the observed geometry of the MS. There are approximately 1300 disc particles in the model Stream, which corresponds to about $2 \times 10^8 M_\odot$ of material, of the same order of magnitude as observational estimates. The simulated Stream is seen to comprise two separate streams, namely a more densely populated main stream which lies close to the position of the actual MS, and a less conspicuous secondary stream to its left. The secondary stream is not actually seen in the neutral hydrogen observations, suggesting some difficulty with the model. This may, however, not be so serious, because the expected surface density in the secondary stream is much lower compared to the main stream. Disregarding the secondary stream, the model MS is relatively broad at its tip and its origin near the ICR. We note that the actual MS shows similar structure. Our success in achieving a more realistic reproduction of the observed morphology of the MS is a notable feature of the present model.

b) The velocity profile

Fig.7 plots the radial velocity seen from the sun corrected for the motion of the LSR with respect to the Galactic Center (V_{GSR}) against the Magellanic longitude defined along the MS by Wannier and Wrixon (1972). (The ‘true’ galactocentric radial velocity is the velocity which would be observed from the Galactic Centre itself, and owing to the small offset of the sun’s position with respect to the Galactic Centre there is a slight difference between this quantity and V_{GSR} . For simplicity, hereafter the ‘galactocentric radial velocity’ is used to mean the velocity seen from the sun but corrected for the solar rotation about the Galactic Centre). Observed velocities for the H I gas are denoted by large diamonds. The model shows reasonable agreement with the observational data. Both the high velocities at the beginning of the MS, about 100 kms^{-1} in the vicinity of the Magellanic Clouds, and the high negative radial velocity of -200 kms^{-1} at the tip of the MS are reproduced.

c) The leading arm feature

Here we mention another interesting aspect of this best model. In Fig.6 (simulation plot in the right panel) an inverse L-shaped leading arm can be seen on the opposite side of the Magellanic Clouds to the MS. This leading arm is more sparsely populated with particles than the MS. We consider that this feature corresponds to the several H I clumps observed by Mathewson, Cleary & Murray (1974) in the area defined by $260^\circ < l < 310^\circ$, $-30^\circ < b < 30^\circ$. The observed H I clumps, though discrete, delineate a similar inverse-L shape whose position on the sky roughly agrees with the model. The positional agreement is not so precise since the simulated ‘arm’ extends to galactic latitudes as high as $b = 60^\circ$. The galactocentric radial velocities of the particles in this simulated leading arm, which range from 100 to 200 kms^{-1} , are somewhat larger than the observed values for H I clumps, in the range 0 to 100 kms^{-1} , but both model particles and H I clumps exhibit a flatter trend in velocity with respect to Magellanic longitude contrasting with the systematic decrease in velocity seen along the length of the MS. The detailed velocity profile and distribution of matter in the leading arm will depend on the form of the LMC potential which appears to be responsible for scattering material of SMC origin into its present location.

A globular cluster, Ruprecht 106, has been discussed by Lin & Richer (1992) as a possible candidate for an object that has been tidally captured from the Magellanic Clouds by the Galaxy. It is actually located in the leading arm region on the sky. However, the observed galactocentric radial velocity of $\sim -233 \text{ kms}^{-1}$ is much lower than that of the H I clouds observed by Mathewson, Cleary & Murray (1974) in this region, which have velocities exceeding 0 kms^{-1} . Therefore, its association with the leading arm is very doubtful. Irwin (1991) reports on four carbon stars near $RA = 13^h$, $Dec = 0^\circ$. In galactic coordinates this corresponds to $l = 310^\circ$, $b = 60^\circ$, a location close to the ‘elbow’ of the leading arm. However, no velocity data is available for these carbon stars for comparison with our best model or the Mathewson *et al.* (1974) observations. Thus the existence of a stellar counterpart to the H I clouds in the leading arm region has yet to be confirmed.

Fig. 6

Fig. 7

4.3 The SMC – Internal structure and kinematics

In the test particle simulation of Paper I it was shown that the existence of the gaseous and stellar bridge between the Magellanic Clouds and the large extent in depth of the SMC could be explained by the creation of a tidal bridge and tail system as a result of the close encounter with the LMC about 0.2 Gyr ago. As we will see in more detail later, our best model also reproduces a basic bridge and tail structure (see Fig.5), with some notable differences from the previous work which result in a better match with several observational features. Since our simulations were carried out including both disc and halo components it is profitable to compare these simulation data with extensive observations of both Population I objects and older populations such as carbon stars and horizontal-branch/clump stars.

a) Appearance of the SMC in the sky plane

We begin by presenting plots showing the neutral hydrogen distribution in the vicinity of the LMC and SMC, and the distributions of disc and halo particles in our best model projected onto the sky plane (Fig.8). For the disc component (middle panel, Fig.8), it is seen that the SMC bar is oriented in a NE-SW direction, coinciding well with the actual orientation of the bar of the SMC on the sky. The disc component shows a boundary in the particle distribution to the SW of the SMC, contrasting with the broad and extended distribution of particles to the east and to the northern direction. This overall distribution is also seen in the H I distribution, which displays a sharp edge in the SW, a bridge of gas extending to the LMC and extensions towards the north which form the beginnings of the MS. It should be pointed out that the disc component does not reproduce the detailed distribution of gas in the ICR, and that the particle distribution between the SMC and LMC is not so sharply concentrated as in the main ridge of the observed gas distribution, which runs along a line of constant declination given by $Dec = -74^\circ$. Also, the edge of the distribution in the SW is not as sharp as in the observed H I distribution. This lack of agreement with the detailed observations could be due to our neglect of gas dissipation processes in our collisionless model.

The halo component (bottom panel, Fig.8) shows a largely circular projected distribution within about 5 degrees of the SMC centre and a distribution of particles extending into the ICR. Gardiner & Hatzidimitriou (1992) found that the projected distribution of horizontal-branch/clump stars, which may be considered to belong to the intermediate-aged population between 2-15 Gyr old, was also largely circular at around distances of 5 kpc from the SMC centre. In their review of the distributions of various population groups, Azzopardi & Rebeiro (1991) pointed out that the older stellar population groups such as carbon stars and planetary nebulae have a rounder and less centrally concentrated distribution than the younger population groups, which are concentrated in the bar. Thus, our simulation of the disc and halo populations is in broad agreement with this general picture. The recent discovery of carbon stars in the ICR by Demers, Irwin & Kunkel (1993), suggests that there may well be stars belonging to the intermediate-aged component displaced into the ICR by tidal forces in agreement with the model. We later discuss the detailed velocity structure of these carbon stars (see Section 4.4).

Fig. 8

b) The 3D structure

Our discussion of the three-dimensional geometrical structure of the SMC is centred on Fig.9, in which we have plotted the distance of the simulation particles from the sun against the angle along the maximum gradient defined by Caldwell and Coulson (1986) (CC), which is in position angle 58° on the sky and runs approximately from NE (negative angle) to SW (positive angle). In the left panel we have plotted the simulation data for the disc component with the Cepheid observations by CC superimposed, while the right panel shows the simulation data for the halo component. In plotting the Cepheid data, we simply assumed that the distance modulus of the coordinate centre used by CC (i.e., $\alpha = 0^h 51^m, \delta = -73^\circ.1$ (1950)) was 18.78 (Feast & Walker 1987) and for each Cepheid we used the difference in modulus from this centre value given in Fig.7 of CC.

The Cepheid observations by CC revealed a large elongation of their distribution along the line of sight. Observations by several other authors (e.g., Florsch, Marcout & Fleck 1981, Laney & Stobie 1986, Mathewson, Ford & Visvanathan 1988) have confirmed a large depth for the SMC and suggested an overall positive gradient in distance from the NE to the SW end of the bar. The disc component in our simulation (Fig.9, left panel) shows a bar highly inclined to the sky plane with the NE end nearer than the SW end in agreement with the general observed trend. Although the spatial orientation of the bar matches the observations, the model seems

to show significantly less elongation than that indicated by the Cepheids, with a model bar 5 kpc long compared to an observed bar about 10 kpc long. This discrepancy may not be serious. Cepheids, being young objects, will better trace the interstellar gas component both spatially and kinematically than will older stellar populations. In the model, the disc particles are treated as collisionless, and hence can be regarded as representing the relatively older stellar population of the disc formed before the start of the simulation at $T = -2$ Gyr. It would not be surprising if the stellar and gaseous components exhibited different dynamical responses, especially in a heavily disturbed region of high gas density. Therefore, a satisfactory detailed modelling of the *internal* structure of the SMC should await a gas-dynamical simulation. It is also seen that the tidal bridge and tail emanate from the far-side and near-side of the bar, respectively. The bridge runs towards negative angle (i.e., to the NE) and continues into the inter-Cloud region. The tail first protrudes to the SW and then turns back to the NE region, extending into the ICR as well. We notice that the bridge and tail features in Fig.9 (left panel) are not as strongly defined as in the Cepheid distribution, presumably due to the lack of dissipation in our collisionless particle model.

The halo component plot in Fig.9, combined with the sky projection plot of Fig.8 (bottom panel) shows that the halo is roughly spherical in the central regions of the SMC at least within 3 kpc of the centre. A very broad bridge and tail structure, less well defined compared to the disc simulation, may be distinguished emerging from the central region. Although the particle distribution is broad, the locus of the bridge section tends to smaller distances with decreasing angle defined by CC, whereas the particles of the tail section are more evenly distributed with respect to angle. This is supported by the fact that for negative angles the ratio of the total number of particles closer than 55 kpc to that beyond 60 kpc is very nearly unity, whereas the corresponding ratio for positive angles is one-third. Therefore the model predicts that the depth of the bulk of the stellar population of the SMC halo would increase and that the mean distance would decrease moving from SW to NE. In the studies of the geometry of the SMC involving the HB/clump stellar populations in the outer parts of the SMC (see Hatzidimitriou & Hawkins 1989, Gardiner & Hawkins 1991, and Gardiner, Hatzidimitriou & Hawkins 1992), the authors found evidence for large depths of up to ~ 20 kpc along the line-of-sight in the eastern part of the SMC, and smaller depths below 10 kpc in the western areas. Furthermore, they reported a corresponding trend towards smaller mean distance moduli in the NE in agreement with the model. A two-component model of the SMC was suggested by these authors in which a nearer component was superimposed on a more distant component in the eastern regions. It is seen from Fig.9 that our best model reinforces such a picture for the eastern region, with the tidal bridge and tail corresponding to the nearer and more distant components, respectively. On the other hand, the SW part is populated mainly by the tail stars, giving rise to a relatively small depth.

Fig. 9

c) Internal kinematics

In Fig.10 we have plotted the heliocentric velocity of the particles with $-78^\circ < Dec < -68^\circ$ against right ascension for both disc and halo components in order to investigate the kinematical structure of the SMC. Firstly, we discuss the disc component (top panel) in relation to a series of figures produced by Mathewson, Ford & Visvanathan (1988) (MFV88) (their Fig.6a-c), which show contours of H I brightness in the velocity-right ascension plane for small (40 arcmin diameter) fields in the central parts of the SMC. In MFV88's Fig.6a and b, which are for regions located in the main bar of the SMC, there is a strong vertical feature at around $RA = 0^h50^m$. It is delineated by both the gas and young stars and presumably corresponds to the velocity field of the bar. The velocity range of this feature is from about 80-200 kms^{-1} and it is slightly tilted such that the eastern part exhibits a higher velocity. This feature corresponds to the large concentration of particles located at similar right ascension in the disc component plot (Fig.10), with a velocity range from 70-220 kms^{-1} . The simulated feature is also tilted in the velocity-right ascension plane in the same sense as the observations. The steep gradient of this feature, which is in excess of 100 $\text{kms}^{-1}/\text{kpc}$ (assuming 1 degree represents approximately 1 kpc at the distance of the SMC) is due to the bar being oriented nearly along the line-of-sight direction. A large velocity gradient will be observed when the bar is seen almost end-on because of the highly non-circular motions along the bar. The tilt in the velocity-right ascension plane is due to the specific geometry of the situation in which larger numbers of approaching (receding) stars are observed along a given line-of sight on the western (eastern) side of the bar given that the particles are rotating clockwise about the SMC centre in the angle-distance plot of Fig.9. The H I distribution in MFV88's Fig.6 (especially b) and c)) shows two distinct velocity components in the main body. This bimodal velocity distribution was not reproduced in the present model, which may be due to our neglect of dissipation and pressure effects inherent in the gas component.

Turning now to the velocity structure of the halo component, we see in Fig.10 (bottom panel) that the velocity feature at around $RA = 0^h50^m$ is a little broader in right ascension with a far smaller tilt than for the disc, indicating the existence of a spherical system supported primarily by random motions in the central regions. This appears to be consistent with the studies of carbon stars by Hardy, Suntzeff & Azzopardi (1989) and planetary nebulae by Dopita *et al.* (1985) which found no evidence of rotation in the central system. In addition to the bar-induced velocity structure in the disc component, we also see the velocity components associated with the tidal bridge and tail in Fig.10 (top panel). The tail protrudes westward from the main bar at a heliocentric radial velocity of $\sim 120 \text{ kms}^{-1}$, and then turns to the east passing the

main bar with increasing velocity up to more than 300 kms^{-1} . The bridge seems to start at a velocity of $\sim 170 \text{ kms}^{-1}$ eastward from the main bar. It should be noted that this latter velocity feature and the start of the tail feature at a velocity of $\sim 120 \text{ kms}^{-1}$ may have observational counterparts in H I features seen at similar velocities in MFV88's Fig.6. In all of their Figs.6a-c, we see a velocity component at $\sim 180 \text{ kms}^{-1}$ extending eastward from the main component, which can be identified with the beginning part of the bridge in our model. Another component at $\sim 120 \text{ kms}^{-1}$ extending westward from the main bar should correspond to the start of the tidal tail in our model. Turning to the halo component plot (Fig.10 bottom panel) it can be seen that the bridge and tail features are broader in velocity than for the disc component and that the tail is relatively weaker. It will be demonstrated later that the extension of the bridge and tail features of the disc and halo components into the ICR may help to provide a good explanation of the complicated kinematics of this area.

Fig.10

d) Velocity-distance correlation

MFV88 and Hatzidimitriou, Cannon & Hawkins (1993) (HCH) have reported the existence of correlations between the distances and velocities of stars in their observed samples. MFV88 found a linear relation between the velocities and distances of some Cepheids observed in the central region and northern part of the bar (see their Fig.12). They found a slope of $4 \text{ kms}^{-1}/\text{kpc}$ for their fit to the data. Hatzidimitriou and her co-workers studied a sample of horizontal-branch/clump stars located at about 3.3 kpc north-east of the SMC optical centre representing an older stellar group than the Cepheids, and also found a linear correlation between distance and velocity but with a larger slope of $8.1 \text{ km}^{-1}/\text{kpc}$. In order to see if our best model can provide an explanation for these correlations we have constructed plots of distance against heliocentric velocity for disc and halo particles lying within $0^h < RA < 2^h$, $-78^\circ < Dec < -68^\circ$ which excludes the inter-Cloud and Magellanic Stream areas (see Fig.11).

It can be seen from Fig.11 that the disc and halo components exhibit a number of common features in the distance-velocity plane. The overall pattern consists of a central feature (the bar in the case of the disc component) between distances of 55 and 60 kpc, a tail section at greater distances and a bridge section at smaller distances. The bridge and tail sections, which are associated with the bridge and tail structures identified in Fig.5, show correlations of increasing velocity with distance. The correlation is less clearly defined for the bridge section than the tail section, but the general trend is nevertheless apparent. For the halo component, there is a

larger velocity spread at a given distance than for the disc, reflecting the greater random motions present in the halo.

We now examine the velocity-distance correlation found by MFV88 for their sample of Cepheids, which we presume to be associated with the disc component. In Fig.11 (top panel), we have superimposed the regression line representing the linear correlation of $4 \text{ kms}^{-1}/\text{kpc}$ found to fit the Cepheid observations. We see a qualitative agreement between this line and the tail section of the disc component. Since the Cepheids lie mostly between distances of 55 and 70 kpc (see Fig.12 of MFV88) we conclude that they are likely to be associated mainly with the SMC's tidal tail structure (see Fig.9).

To investigate the velocity-distance correlation observed by HCH for HB/clump stars we consider the halo component plot (Fig.11 bottom panel), since these stars belong to the intermediate-aged population in the SMC. On this plot we have superimposed the fit obtained by HCH for the stellar observations, which we have indicated by the solid line. Although the particle distribution is broad, the observational regression line of $8.1 \text{ kms}^{-1}/\text{kpc}$ roughly matches the distance-velocity trend in the bridge section. A steeper slope in the distance-velocity plane, corresponding to a gradient closer to the value of $4 \text{ kms}^{-1}/\text{kpc}$ obtained for the Cepheid sample of MFV88, would appear to give a better representation of the particle trend. In fact, a linear fit to the simulation data for particles between 40 and 55 kpc gives a correlation of $3.4 \text{ kms}^{-1}/\text{kpc}$. We note here that HCH's stellar sample consisted only of stars with distances less than 60 kpc, which was caused by a selection effect due to the rejection of more distant stars with low signal-to-noise ratios in the original sample. The stars in HCH's sample therefore appear to lie mostly in the bridge feature. A rather stronger velocity-distance correlation for the halo component is seen in the tail section at distances greater than 60 kpc. It would certainly be interesting to see if HB/clump stars at larger distances (for which HCH failed to get data of sufficient quality during their observing run) match the velocity-distance correlation seen in the simulated tidal tail.

On the basis of the existence of velocity-distance trends in the best model which may be approximately fit by gradients similar to observed values, we suggest that the origin of the velocity-distance correlations is connected with the tidal distortion of the SMC induced by the last close encounter between the Magellanic Clouds about 0.2 Gyr ago.

Fig.11

We now discuss aspects of the simulation of the disc and halo components for our best model relating to the kinematics of gas and stars in the region between the Magellanic Clouds, namely the inter-Cloud region. Kunkel, Demers & Irwin (1994) (KDI) have investigated the kinematics of carbon stars in the ICR and compared their observations to those of early-type stars and neutral hydrogen. They also conducted numerical simulations to investigate the observed velocity trends. Their Fig.5 shows the galactocentric radial velocities (V_{GSR}) of carbon stars, early-type stars and H I peaks plotted against their angular distance from the SMC centre. In order to compare these observations to our best simulation we found it instructive to construct a similar plot for the disc and halo simulation data (Fig.12). We made plots for the disc (top panel) and halo (bottom panel) particles within the quadrant centered on the position angle of the LMC with respect to the SMC centre to exactly correspond to the area of sky included in KDI's figure.

In KDI's Fig.5 the H I velocity peaks are seen to span a wide range in galactocentric velocity from -20 to 90 kms^{-1} at 5 degrees from the SMC centre to a range of 0 to over 150 kms^{-1} at 15 degrees. Our disc component shows a distribution in velocity which is a little broader, from $-50/130 \text{ kms}^{-1}$ at 5 degrees to $-50/200 \text{ kms}^{-1}$ at 15 degrees from the SMC centre, but which agrees remarkably well with the general trend in the velocity pattern. KDI noted that the majority of carbon stars were found at negative or low galactocentric velocities, whereas it can be seen from their Fig.5 that the early-type stars are more evenly distributed within the velocity range defined by the H I envelope. KDI performed some interpretive numerical simulations which produced a bridge and tail structure for the SMC. As already mentioned in Section 4.1, these features appear to be related to the tidal bridge and tail structure in our best model. On the basis of their simulation they suggested that the carbon stars belonged mainly to the bridge section, while the H I gas belonged mainly to the tail section, some mechanism being proposed that removes or ionizes the neutral gas in the bridge in order to account for the observed deficiency there. In our scenario, however, we contend that the H I gas is associated with both the bridge and tail sections, not just the tail, and we explain the difference in the velocity distribution of young (H I gas and early-type stars) and old (carbon stars) population components based on the separate kinematics of the disc and halo components.

Our explanation for the distribution of carbon star velocities compared to that of the younger populations is as follows. We have previously stated that the ICR is populated by the particles of the tidal bridge and tail. Comparing the disc and halo components plotted in Fig.12, we can clearly identify the velocity pattern due to the bridge and tail at lower and higher galactocentric velocities respectively in the disc component plot, while in the halo component plot the bridge is apparent but the tail is very weak. By counting particles at angular distances between 3.5 and 15 degrees from the SMC centre, and ascribing particles with velocity less than 50 kms^{-1} to the bridge and those with greater velocity to the tail, we could determine the relative numbers of particles in the bridge and tail for the disc and halo components. It was found that the bridge/tail particle number ratio was 1.4 for the disc and 3.3 for the halo. Confining the distance range to 5-10 degrees leads to corresponding ratios of 1.8 and 3.6. Thus it is apparent

that the bridge is dominant in the halo component, and therefore our model predicts that the carbon stars, which are probably associated with the halo population, are more likely to be found in the bridge, while the early-type stars (and HI gas), presumably associated with the disc component, are likely to be found in both the bridge and tail sections, in good agreement with the observations. Although the halo component did generate a tidal tail (see Fig.5b) the tail is not as well developed as the tidal tail from the disc component in the inter-Cloud region.

Fig.12

5 CONCLUSIONS AND FUTURE WORK

We have carried out an extensive set of numerical simulations of the tidal distortion of the SMC due to the Galaxy and LMC. A barred galaxy model was taken to describe the SMC at the beginning of the interaction simulation well before the close encounters with the Galaxy and LMC take place. The effect of particle self-gravity was taken into account for the SMC model. Our study is not meant to be a complete survey of the whole permissible parameter space. However, by proceeding rather heuristically, we succeeded in obtaining a model which explains many observational characteristics of the Magellanic system. The major achievement of the present model is that it has been able to provide the most coherent explanations to date of various structural and kinematical properties of the SMC and related tidal features without resorting to other non-tidal effects such as ram pressure or collisions with high velocity clouds.

The main results are summarised as follows.

1. Our best model has succeeded in reproducing the observed morphology of the Magellanic Stream including the general form of the variation of the width of the Stream from its origin to its tip. The velocity profile of the H I gas was also reasonably well matched by the simulation.
2. We provide support for the idea of a leading arm on the opposite side of the Magellanic Clouds to the Magellanic Stream, by identifying a feature in our simulation which corresponds to the scattered H I clumps at $260^\circ < l < 310^\circ$, $-30^\circ < b < 30^\circ$ observed by Mathewson, Cleary & Murray (1974).
3. We have achieved a fairly good reproduction of the observed morphology of the SMC bar on the sky plane and its spatial orientation along the line-of-sight, although the full extent of the bar and narrow spiral arms observed for Cepheids by Caldwell & Coulson (1986) were not reproduced. The underlying kinematical structure of the central regions was shown to be caused by the velocity pattern induced by a bar seen almost end-on.

The following three results are based on a detailed examination of the tidal bridge and tail structure which was formed as a result of the close encounter between the SMC and LMC $\sim 2 \times 10^8$ years ago. The outer extension of the tail and bridge constitute the inter-Cloud region.

4. The halo component in our model appears to show a trend of increasing depth from SW to NE in agreement with studies of the 3D distribution of horizontal-branch/clump stars in the outer parts of the SMC (i.e., 2-5 kpc from the optical centre) by Hatzidimitriou & Hawkins (1989). This is because the tidal tail and bridge are both seen superposed in the NE region on the sky, whereas the SW region predominantly comprises stars which belong to the tail.

5. Our model has succeeded in reproducing the correlation between distance and velocity found for samples of Cepheid stars observed by Mathewson, Ford & Visvanathan (1988) and horizontal-branch/clump stars observed by Hatzidimitriou, Cannon & Hawkins (1993). The Cepheid sample is probably associated with the tidal tail, and the HB/clump star sample mainly with the tidal bridge.

6. For the inter-Cloud region, the velocity pattern observed for young objects (neutral hydrogen, early-type stars) and older objects (carbon stars) showed much correspondence with the simulated velocity pattern for the disc and halo components, respectively. The disc component developed both a tidal tail and a bridge, providing a natural explanation of the wide velocity range observed for the neutral gas and the early type stars. On the other hand, the halo mainly developed a tidal bridge with the tail being significantly weaker. This may explain the concentration of carbon stars at low galactocentric velocities (which correspond to those of the bridge) found by Kunkel, Demers & Irwin (1994).

Although the present numerical study succeeded in explaining many observed structural and kinematical peculiarities of the SMC and related features within a purely gravitational framework, we still note several discrepancies. These discrepancies are mainly related to the young stellar objects and the gaseous component of the SMC. For example, the existence of two main velocity components in the neutral hydrogen distribution of the main body of the SMC (Mathewson & Ford 1984) was not reproduced. We also failed to simulate the narrow concentration of gas in the inter-Cloud region which forms the gaseous belt between the Magellanic Clouds. In addition, the observed spatial distribution of the Cepheids (Caldwell & Coulson 1986) delineates much sharper structures and the bar is much greater in extent than the model suggests. It will be quite interesting to see if an adequate gas-dynamical model which incorporates the dissipative and collisional nature of the interstellar gas as well as associated star formation processes can solve these problems. We are now preparing such a study using a cloud-particle scheme for the interstellar gas model.

Another promising line of future study is to simulate the dynamics of the LMC (instead of the SMC) using our self-gravity numerical code. Although material from the LMC is considered to make a smaller contribution to the formation of the Magellanic Stream and the inter-Cloud region, the internal dynamics of the LMC itself are quite intriguing. The interstellar gas shows

a non-symmetrical spatial distribution around the LMC bar, and two velocity components are also observed (the L- and disc- components of Luks & Rohlf 1992). It will therefore be a major goal of a future study to explain these peculiarities in the LMC as the outcome of the Galaxy-LMC-SMC interaction.

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FIGURE CAPTIONS

Figure 1. Schematic view of the Galaxy and the Magellanic Clouds, showing the relationship between the standard galactocentric coordinate system (X, Y, Z) and the non-inertial SMC-centric system (x, y, z) used for the computations. The relationship between the two coordinate systems is specified by the angles θ and ϕ defined by the rotation axis of the SMC with respect to the galactocentric system.

Figure 2. Equilibrium model of the SMC. Projections of the particle positions on the $x - y$ and $x - z$ planes of the SMC-centric coordinate system for both disc and halo components are shown. Distance units are indicated in kpc.

Figure 3. SMC-centred ‘orbits’ of the Galaxy and the LMC for simulations with $\theta = 45^\circ$, $\phi = 230^\circ$. The paths traced by the Galaxy (dashed curve) and the LMC (solid curve) from $T = -2$ Gyr to the present are indicated for SMC-centric $x - y$ (x abscissa), $x - z$ (x abscissa) and $y - z$ (y abscissa) projections, with distance units in kpc. The direction of motion is shown with arrows as well as the positions at which the LMC-SMC distance is at local minima at $T = -1.40$ Gyr (filled circle) and $T = -0.18$ Gyr (open circle). The SMC initially rotates counter-clockwise in the $x - y$ plane. The bottom right hand plot shows the Galaxy-SMC and LMC-SMC distances as a function of time.

Figure 4. The tidal force exerted on the SMC by the Galaxy and the LMC as a function of time. The tidal force was calculated from the double derivative of the Galaxy and LMC potentials at the position of the SMC (see text for explanation).

Figure 5. Global view of the best model at $T = 0$ (the present epoch). The position of the LMC is indicated by an open circle.

(a) Disc component. The disc particles are shown projected onto the SMC-centric $x - y$ plane with distance units in kpc. Major structures are labelled.

(b) Halo component. The halo particles are shown projected onto the SMC-centric $x - y$ plane with distance units in kpc.

Figure 6. Simulation of the Magellanic Stream. The neutral hydrogen distribution (left panel) and the distribution of disc particles in the best model (right panel) are shown projected onto the sky plane. Observational data for the Magellanic Stream is taken from Mathewson & Ford (1984), and the H I clumps observed by Mathewson, Cleary & Murray (1974) are also shown indicated by the thicker curves.

Figure 7. The velocity profile of the Magellanic Stream. The variation of the GSR (galactic standard of rest) velocities of the disc particles in the best model is shown as a function of Magellanic longitude defined by Wannier & Wrixon (1972). Also shown are the observational data of Mathewson, Cleary & Murray (1974) represented by diamonds.

Figure 8. Comparison of the neutral hydrogen distribution in the vicinity of the Magellanic Clouds with the particle distribution of the best model. Top panel: the surface density of H I from Fig.2 of Mathewson & Ford (1984). The contour levels correspond to 5, 10, 20, 40, 75, 150,

400 in units of 10^{19} atoms cm^{-2} . This map is meant to roughly illustrate the neutral hydrogen distribution near the LMC and SMC, and in the inter-Cloud region, so that some small clumps at the periphery are omitted. Middle panel: the distribution of disc particles in the best model plotted on the plane of the sky. Bottom panel: the halo particle distribution.

Figure 9. The 3D structure of the SMC. The heliocentric distances of the disc (left panel) and halo (right panel) particles of the best model are plotted against the angular distance along the direction of maximum distance gradient found by Caldwell & Coulson (1986), which is in position angle 58° and runs approximately from NE to SW with increasing angle. The distances of Cepheid variables from this study are also plotted in the left panel (open circles with error bars).

Figure 10. The velocity pattern in the SMC. The heliocentric particle velocities of the best model are plotted against right ascension for the disc (top panel) and halo (bottom panel) components. Only the particles with $-78^\circ < Dec < -68^\circ$ are plotted. Compare with Fig.6 of Mathewson, Ford & Visvanathan (1988).

Figure 11. The velocity-distance correlation in the SMC. The heliocentric distances of particles of the best model lying within $0^h < RA < 2^h$, $-78^\circ < Dec < -68^\circ$, are plotted against their heliocentric velocities for the disc (top panel) and halo (bottom panel) components. The fit representing the velocity-distance correlation, with a slope of $4 \text{ kms}^{-1}/\text{kpc}$, found for a sample of Cepheids by Mathewson, Ford & Visvanathan (1988), is indicated in the top panel. The fit representing the velocity-distance correlation, with a slope of $8.1 \text{ kms}^{-1}/\text{kpc}$, found for a sample of horizontal-branch/clump stars by Hatzidimitriou *et al.* (1993), is indicated in the bottom panel.

Figure 12. The velocity pattern in the inter-Cloud region. The galactocentric radial velocities of particles of the the best model lying within the quadrant centred on the position angle of the LMC are plotted against angular distance from the SMC centre for the disc (top panel) and halo (bottom panel) components. Compare with Fig.5 of Kunkel, Demers & Irwin (1994).